A Further Study of the So-Called Horopter, Making Ocular Rotations Easy of Understanding.

19

G. C. SAVAGE, M.D.
Professor of Ophthalmology, Medical Department of Vanderbilt University.
NASHVILLE, TENN.

Read at the Twelfth Annual Meeting of the American Academy of Ophthalmology and Oto-Laryngology, held at Louisville, Ky., Sept. 26-28, 1907.

[Illustrated.]

Reprinted from the Ophthalmic Record, December, 1907.

A FURTHER STUDY OF THE SO-CALLED HOROPTER, MAKING OCULAR ROTATIONS EASY OF UNDERSTANDING.

G. C. Savage, M.D.
Professor of Ophthalmology Medical Department of Vanderbilt University,
NASHVILLE, TENN.

(Illustrated.)

In his study of optics. Helmholtz made three fundamental errors from which he was never able to free himself. One of these errors was the construction of the optic axis by beginning at the center of the cornea, making this point the anterior pole, carrying it back through the center of rotation and on to the retina, at a point between the macula and disc, making this point the posterior pole. The second error, growing out of the first, was his faulty construction of the visual axis by carrying it from the macula forward, on the temporal side of the center of rotation, to the nodal point, thence through the cornea to the nasal side of the anterior pole, on into space. The third error, growing out of the first and second, was his conclusion that all lines of direction are the axial rays of cones of light which, he taught, cross each other at the nodal point, a few millimeters in advance of the center of rotation. To these fundamental errors is chargeable the fact that no man, not even his brightest pupil, has been able to understand Helmholtz's chapter on the "Rotations of the Eyes." Even he himself must have recognized the murkiness of this chapter, for, when one of his brightest students said to him, "Professor, I have no trouble with any part of your 'Physiologic Optics' except the chapter on 'Rotations of the Eyes,'" he replied, "I am not astonished to hear you so speak. Leave that chapter alone, for, though it cost me more time and

thought than any other part, I must rewrite it; then I hope to make it clear." He lived twenty or more years after this conversation, but never rewrote his chapter on "Rotations of the Eyes." If he had been fortunate enough to have discovered the fundamental errors pointed out above, he would have rewritten this chapter and would have made it so strong and clear that no student could fail to understand. With these errors eliminated, ocular rotations are as easy of comprehension as the simplest problem in geometry, which, indeed, it is.

Helmholtz's greatness made his mistakes more fatal, for the world stood ready to accept his teachings as scientific truths, nor was the world often disappointed. To controvert him, while he was alive, would have been considered audacious, and no one knows better than I do the hard task one has who dares, even now, to teach for scientific doctrine anything contrary to the dictum of Helmholtz. In admiration of the greatness of Helmholtz allow me to say I am second to no man. His portrait hangs on one of my walls and is an inspiration to me. I ought to love him, if for no other reason, because of the three errors from which he could not free himself, otherwise *Ophthalmic Myology* and *Ophthalmic Neuromyology* would never have been written.

In order that the horopter (better the Maddox isogonal circle) may be understood and its full significance may be appreciated, the conditions underlying binocular single vision must be known, for without the power of binocular single vision (impossible to some) there can be no monoscopteric circle.

The supreme law of binocular single vision is the law of corresponding retinal points. The law of direction does not make corresponding retinal points, else the two images of any one point would always result in single vision, regardless of the relationship of the visual axes and the horizontal retinal meridians to the plane of the primary isogonal circle. To illustrate: It must be conceded that a point and its two images lie in the plane of the same isogonal circle, under normal conditions of refraction. A line of direction goes from the image in each eye and the two intersect at the point, and of necessity they both lie in the plane of the circle containing the three points. Each of these lines is a radius of retinal curvature prolonged and, therefore, the point at which they intersect

should be always single, regardless of the relative position of the two eyes, if the law of direction creates binocular single vision. If one eye is turned up or down, the point and its two images still lie in the same plane, and the two lines connecting the two images with the one point are radii of retinal curvature prolonged, but the point is not seen single; therefore, there must be a law for corresponding retinal points other than the law of direction.

This law of corresponding retinal points is founded on an anatomic and not on a psychologic basis. If the cones of the central points of the two maculas have not a common brain connection, binocular single vision is impossible. To simplify: Let us suppose that there is but one cone constituting the *fovea centralis* of each macula; the axone going from this cone in the one eye will pass backward toward the brain and will meet the axone from the foveal cone of the other eye, at the beginning of the one tract or the other. One of the axones having crossed, by way of the chiasm, to meet its fellow from the other fovea, they then go side by side to the corresponding cuneus and terminate in one cell in the cortex of that cuneus. The impression of light on these two cones would be a double impression, but these would be transmitted to the one cell and could excite but a single sensation. If the cones of the two foveas have the proper brain connection, it can be easily conceded that there is no faulty connection of the cones of the two maculas, and that the rods and cones of the two retinas, point for point, have common brain connections. The vertical and horizontal retinal meridians cross each other in their respective foveas. If these points of crossing correspond, that is, have a proper brain connection, then the two vertical meridians will correspond point for point, as will also the two horizontal meridians throughout their entire extent. What is true of these two cardinal meridians must be true of any two oblique meridians which bear a similar relationship to the cardinal meridians, as the two meridians at 45°.

If Helmholtz's law of direction, namely, that the lines of direction are axial rays, were true, corresponding retinal points in any two corresponding meridians would have to be measured in millimeters from the foveas, and not in degrees of arc, for the angle of any two lines crossing at the nodal point would neither be an inscribed angle nor an angle at the center of the retinal curve; there-

fore, it is not measured by either the half or the whole of the intervening retinal arc. A glance at Figure 2 will show this. It is true that the angle B-n-A in this faulty figure, being an inscribed angle, is measured by half the arc B-A, and the angle c-n-b is equal to the angle B-n-A, for they are opposite angles, but it is not true that half the arc B-A is equal to the whole retinal arc c-b. If we must measure the distance of retinal points from the fovea by millimeters, we should measure the distance between spacial points by meters and not by degrees. Most authors who have not rejected Helmholtz's axial-ray theory have been consistent in that they have measured corresponding retinal points in millimeters from the fovea, but have been inconsistent in that they have measured the distance between spacial points in degrees.

Helmholtz was wrong in teaching that axial rays are lines of direction, and this error grew out of his first and greater error, the incorrect location of the poles of the eye. These errors are alike in that he began at the cornea and worked backward to the retina. He should have started at the retina and then worked forward. It must be universally conceded that the retinal meridians all cross each other at the fovea, nor can it be denied that this point of crossing must be the posterior pole of the eye. How easy now to construct the optic axis by extending a line from the posterior pole through the center of retinal curvature (the center of rotation) to the cornea, and thus find the anterior pole, a course directly opposite the one pursued by Helmholtz. The anterior pole thus located is usually to the nasal side of the center of the corneal curve, but in ideal eyes it coincides with the center of the corneal curve. In all eyes the posterior pole is the fovea centralis, but the anterior pole may or may not be the center of the corneal curve. (The real anterior pole is in the aqueous chamber, just as far in front of the center of rotation as the fovea is behind it.) In every eye the antero-posterior axis, or optic axis, prolonged is the visual axis, as distinguished from all other visual lines. This line is a radius of retinal curvature prolonged, and so are all other lines of vision. Otherwise an isogonal spacial circle with corresponding retinal arcs could not be constructed. The true law of direction, therefore, must be this: *"Every line of direction is a radius of retinal curvature prolonged."*

Thus stand corrected Helmholtz's three fundamental errors—first, his error in locating the poles; second, his error in constructing the visual axis, and, third, his error of conception that lines of vision are axial rays of light. One holding to these errors can have no clear conception of the primary isogonal circle (horopter), without which there can be no correct understanding of either monocular or binocular rotations. The chapter that Helmholtz would have written on "Rotations of the Eyes," if these three errors had not made his mind murky, can only be conjectured, but I am willing to concede that he would have surpassed any author preceding or following him.

I was not hunting for Helmholtz's errors when I found the true principles of the horopter or isogonal circle, but the light of the truth revealed his errors. Only a few weeks before his death he dictated a letter to me in which he expressed an interest in my then earlier writings. If he were living now I believe he would count himself happy in that an admirer had pointed out his three fundamental errors, and I know that he would have counted himself thrice happy if he could have found them himself.

Soon after *"New Truths in Ophthalmology"* came from the press I was asked, "Have you read LeConte on *'Sight'?"* I was forced to answer I had not. I procured a copy and read it with eagerness. When I had read "The rods and cones see ends on" and "For every retinal curve there is a corresponding spacial curve," it seemed to me that LeConte not only agreed with me that every line of direction is a radius of retinal curvature prolonged, but that he had antedated me in its publication. I did not feel myself confirmed in this view when I saw his horopter, here reproduced, in Figure 1, from his first edition. I reasoned that the rods and cones all pointed to the center of retinal curvature, and that, "seeing ends on," the line of sight must be a radius of retinal curvature prolonged. I knew that "retinal and spacial curves" could not correspond unless they were concentric, so that a line connecting any two points corresponding in degrees must pass through the common center, hence must be a radius of retinal curvature prolonged. In spite of his faulty horopter (Fig. 1), I was ready to give LeConte credit for a great discovery and so wrote him, sending what I had written on the same subject. To my surprise, his reply stated that

he had only spoken poetically and graphically when he stated that "the rods and cones see ends on." for he believed with Helmholtz that all lines of direction are axial rays. and that they cross each other at the nodal point. He further stated that my letter had called his attention to the fact that the horopter in his first edition

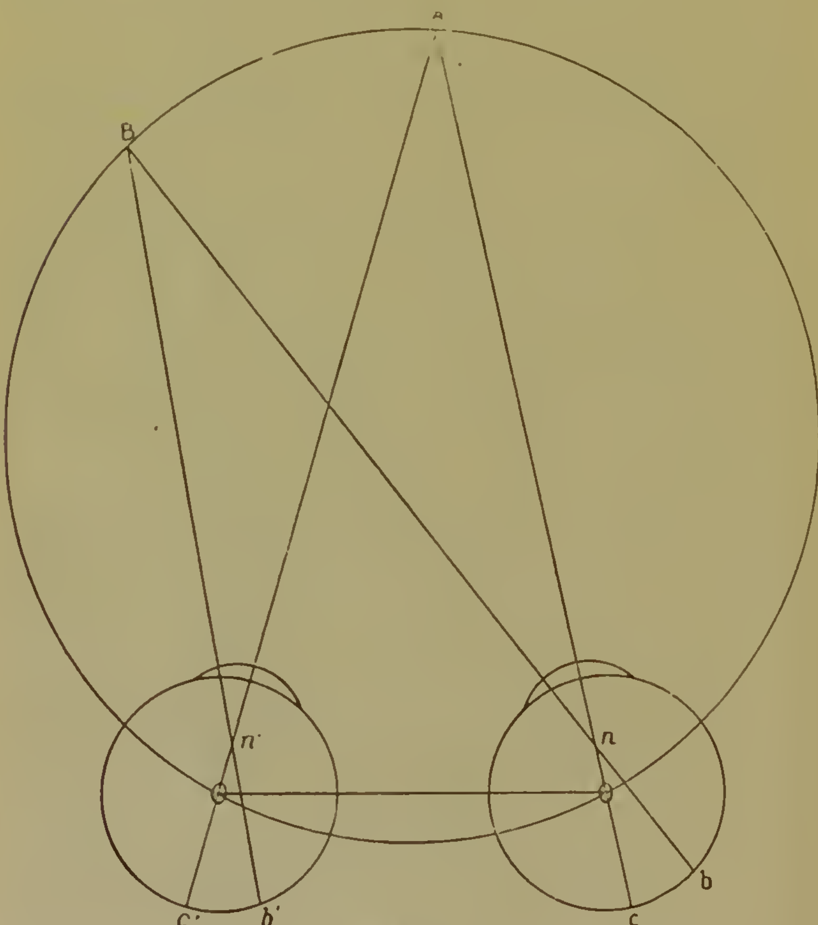

Figure 1.

of *"Sight"* was incorrect in that the circle passed through the centers of rotation (Fig. 1) when it ought to have passed through the nodal points. To be consistent, he had to remodel his horopter, which he did in his second edition of *"Sight,"* and this remodeled horopter is here reproduced in Figure 2. which, as already shown,

is not a mathematical figure and, therefore, can not be the true horopter (isogonal circle).

To put it mildly LeConte's disclaimer staggered me and made me doubt for a moment the correctness of what I had published

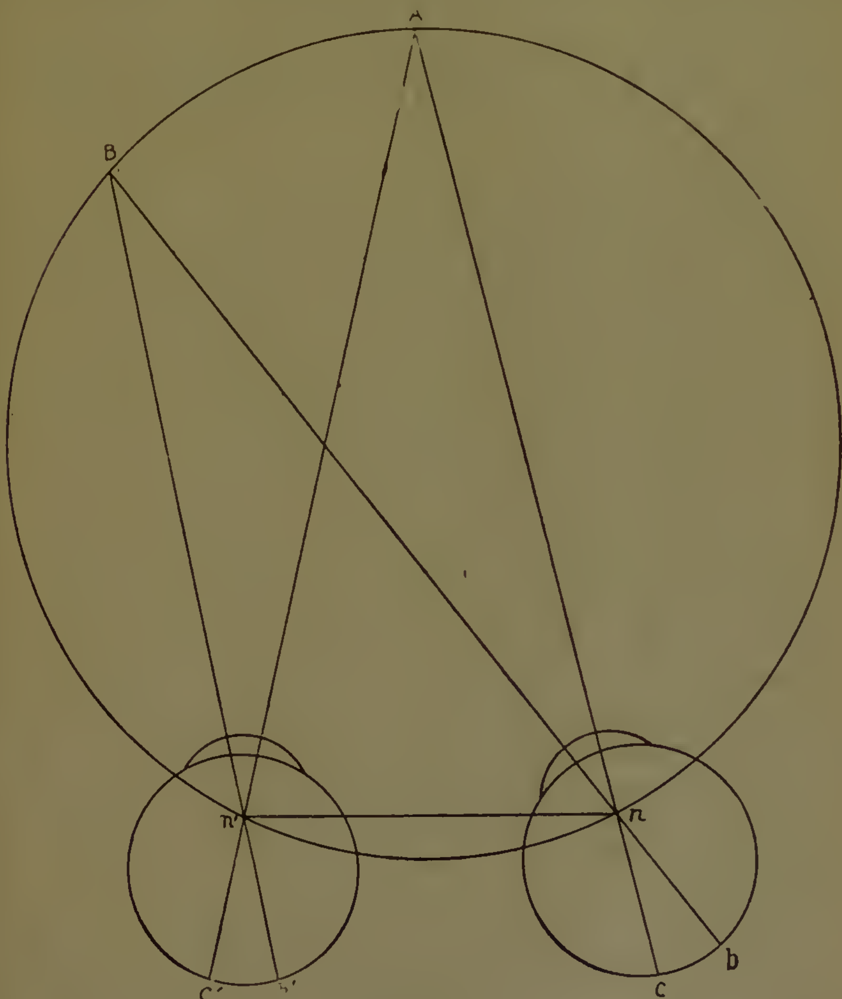

Figure 2.

concerning the law of direction. I have no explanation for his holding to Helmholtz's errors after his attention had been called to them and after he apparently had discarded them in the two quotations made above. But further study convinced me more

fully that Helmholtz had perpetrated these three fundamental errors, and that LeConte had perpetuated them.

It is cruel to kill a pet with a point. The fatal point I present against the Muller horopter, the Figure 2 from LeConte, is that, if a rotation from A to B is attempted, one of two things must happen: Either the two nodal points will leave the circle, for they are in advance of the center of rotation: or the circle, moving to the left with the eyes, will leave both the first and second points of view. Take either horn of the dilemma, and the value of the circle is destroyed.

Because binocular single vision and both monocular and binocular rotations could not be clearly understood, in the light of the teaching of Helmholtz and a host of his followers, I sought the more earnestly for the correct principles underlying them. These fundamental truths are: (1) The visual axis is the true antero-posterior or optic axis, the posterior pole being the central point of the macula; (2) all lines of vision intersect the visual axis at the center of retinal curvature, which is the center of rotation, and, like the visual axis, are radii of retinal curvature prolonged; (3) the cone at the posterior pole of one eye corresponds with the cone at the posterior pole of the other eye, for the reason that these have a common brain-cell connection in one cuneus; that all other corresponding retinal points are either rods or cones with a common brain-cell connection, either in the one or the other cuneus; that these corresponding points compose the corresponding retinal meridians, and that corresponding points are related, each to its own fovea, by degrees of arc and not by millimeters.

The above fundamental truths are essential to a clear understanding of binocular single vision and of monocular and binocular rotations.

On the spherical concavity of the retina is founded the mental law of direction, which is : *"Every line of direction is a radius of retinal curvature prolonged."* The spherical concavity of the two retinas and the law of direction create the mathematical circles of possible binocular single vision. These circles are innumerable and must be divided into two classes. Belonging to the first class there is only one circle, the primary, but to the other class belong an infinite number of circles, the secondary. Each of the secondary

circles has the same radius as that of the primary circle, and all of these are bisected by the extended median plane of the head. All of these circles have two points in common; that is, the centers of retinal curvature which are the centers of rotation of the eyes, but the third point through which each independent circle is constructed lies in the extended median plane of the head, each being the same distance from the center of the cord common to all (the line connecting the centers of the two eyes), as is the point of direct fixation on the primary circle. Each of these circles has its own plane, and all these planes intersect in the cord connecting the two centers of retinal curvature. In each of these planes lie innumerable lines of direction from each eye, one from one eye intersecting one from the other eye at every point on the circle. The angle of intersection for any two lines is precisely the same as the angle of intersection of any other two lines, for each is an inscribed angle and is measured by half of the same arc.

A point on any one of these circles is seen single with the two eyes only when the intersecting visual lines come from rods or cones in the two retinas which have a common connection with a single brain cell in one cuneus. These rods and cones constitute corresponding retinal points. Corresponding retinal points and the relationship of the vertical axes of the eyes to the median plane of the head do not create the isogonal circle. These become monoscopteric circles only when the two visual axes and the horizontal retinal meridians are made to lie in the plane of the primary circle with the visual axes converging at some point on this circle. With one visual axis in the plane of the primary circle and the other in the plane of a secondary circle, either below or above the primary plane, means diplopia everywhere. With the visual axes both lying in the plane of the primary circle, but intersecting within or beyond the circle, means diplopia everywhere. Let the planes of the horizontal retinal meridians fail to lie in the extended plane of the primary isogonal circle, the vertical axes of the eyes either diverging or converging above, can only mean diplopia everywhere,[1] but if the vertical axes should lean towards the right or towards the left.

1. In non-symmetric oblique astigmatism the distortion of images compels convergence or divergence of the vertical axes, in the interest of binocular single vision, but at the expense of correct orientation.

the same number of degrees, there would be no diplopia, but there would be loss of correct orientation.

The law of corresponding retinal points is supreme and imperious, as related to the isogonal circles, both the primary and secondary. The behests of this law are obeyed by the extrinsic ocular muscles, in the interest of binocular single vision and correct orientation. If the two visual axes are made to lie in the plane of the primary isogonal circle, when in its primary position, by watchfulness of the basal centers in control of the superior and inferior recti muscles, and are made to intersect at a point on this circle, at the intersection of the extended median plane of the head, by the action of the third conjugate center on the interni, aided, if necessary, by the basal centers connected with either the externi or interni, and if the horizontal retinal meridians are forced by the obliques to lie in the plane of the primary isogonal circle extended backward, then this isogonal circle is converted into a monoscopteric circle. As a result of this planing and converging of the visual axes, and the planing of the horizontal retinal meridians, every point on all the secondary isogonal circle is seen single; hence these circles all become monoscopteric. The sum of all of these points makes the monoscopteric surface, shown in this model.[2]

Every point in the field of binocular vision, not in the plane of the primary isogonal circle, lies in the plane of some secondary isogonal circle and also in the extended plane of some retinal meridian, either the vertical or an oblique meridian, and on the line of intersection of these two planes, which is the line of vision for that point. Any one of these points may become the secondary point of view, which means that the two eyes can be so rotated as to bring the two maculas under the two images of the secondary point. In doing this, the visual axes have simply taken the places of the two indirect visual lines which had connected the one point with its two retinal images.

The purposes to be accomplished by the twelve ocular muscles are: first, binocular single vision, with which all of them are concerned; second, range of vision, with which the lateral recti alone are concerned; third, extent of vision, with which all the recti and the

2. The surface exhibited in wood was that generated by revolving the primary circle up and down on the cord connecting the centers of the two eyes, as shown in Figure 3.

obliques are concerned, and, fourth, correct orientation, with which the obliques are chiefly concerned. All of these purposes are accomplished in obedience to a law that governs both binocular rest and binocular motion. That this law may be understood there are three things that must be well in mind: first, the primary isogonal circle; second, the visual axes, and, third, the horizontal retinal meridians. To ignore the first is to fail to comprehend the import of the second and third; hence a knowledge of the primary isogonal circle (the old horopter) is supremely important. It must not be forgotten that to change the point of direct view is to create a new primary isogonal circle, and, since there is an infinite number of points in the line of intersection of the extended median and horizontal planes of the head, there can be an infinite number of primary isogonal circles, only one of which can have a real existence at one and the same time. They are all alike in that each is constructed through the centers of rotation (two fixed points) and the point of direct fixation (a variable point), and that they must lie in a common plane. Likewise in the extended plane of each secondary isogonal circle there may be constructed an infinite number of secondary circles, each differing from the other only in the length of its radius. Still another thing must be known; that is, there is no point in the binocular field that does not lie in either the plane of the primary isogonal circle or in the plane of one of the secondary isogonal circles. And still another fact must not be ignored: that is, the planes of all isogonal circles intersect in the line connecting the centers of rotation of the two eyes, which line is a cord common to all the circles. All of these things necessary for a proper understanding of the law of binocular rest and motion are easy of comprehension, but not easier than is the understanding of the law itself, in the light of these facts.

The following is the law of both binocular rest and motion:

THE OCULAR MUSCLES MUST SO RELATE THE TWO EYES THAT THE TWO VISUAL AXES AND THE TWO HORIZONTAL RETINAL MERIDIANS SHALL ALWAYS LIE IN THE PLANE OF THE PRIMARY ISOGONAL CIRCLE, AND THAT THE TWO VISUAL AXES SHALL INTERSECT AT SOME POINT ON THIS CIRCLE, IN THE

INTEREST OF BOTH BINOCULAR SINGLE VISION AND CORRECT ORIENTATION.

That the above law may be obeyed, every rotation plane must be a meridional plane extended, and the equatorial plane must contain the axis of every rotation. A study of Figure 3 will show that, in direct rotations to the right or left, the plane of the primary circle is not moved, but the visual axes are shifted with unvarying

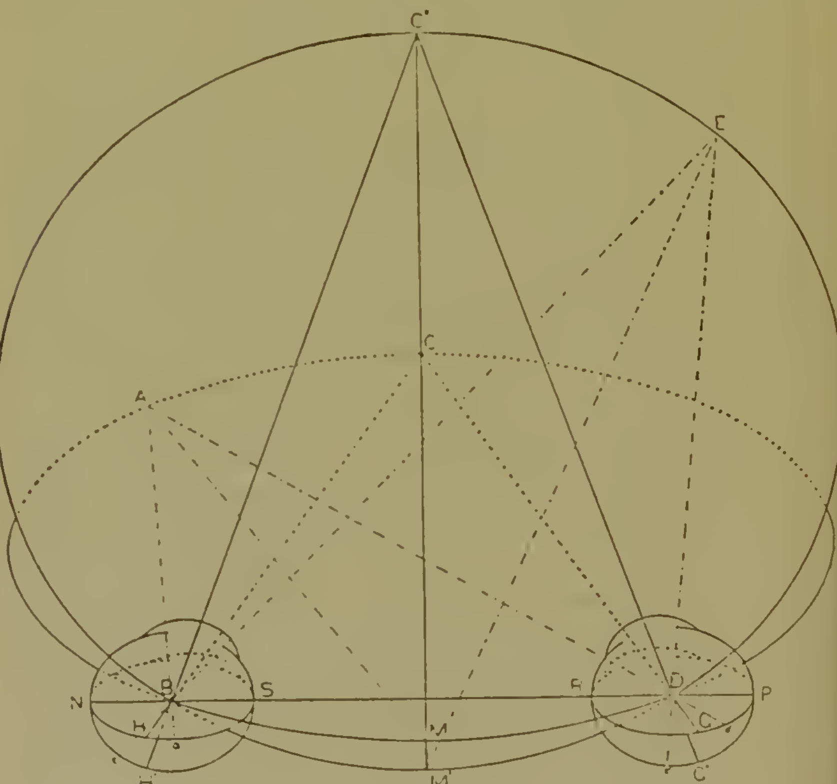

Figure 3.

angle in this plane from point to point as from C to A. It will also be seen that in passing from the primary point of view (C) to a point directly above (C′) or below, on a secondary circle, the primary plane (B-C-D) is made to take the place of the secondary plane (B-C′-D), but the visual axes have not been shifted in it. While unmoved in the plane of the primary circle throughout the rotation of the latter, each axis has moved in the extended plane of its own

vertical meridian from the primary to the cardinal secondary point of view, the angle of convergence unvarying.

Again, Figure 3 shows that, when fixation is to be changed from the primary to an oblique secondary point (from C to E), the plane of the primary circle B-C-D is made to take the place of the plane of the secondary circle B-C′-D, and the visual axes H-C and G-C are made to assume the positions of the indirect visual lines E-e and E-e′. During the rotation of the primary plane neither the visual axes nor the horizontal retinal meridians have been allowed to leave it, but both have been shifted in it, each visual axis moving in the plane of that retinal meridian extended in which were located the point and its image before the rotation began.

H, the image of C, is on the macula, at the point of intersection of the vertical and horizontal retinal meridians, while C is on the line of intersection of the extended planes of these meridians. But since the plane of the primary isogonal circle and that of the horizontal retinal meridian coincide, it is easily shown that every object in the binocular field of vision and its retinal image are on the line of intersection of some one isogonal plane and the plane of some one retinal meridian; therefore, the object in the spacial concave occupies the same relationship, in degrees, to the vertical and horizontal retinal meridians extended, as its retinal image in the retinal concave does to these meridians. The line connecting the two is the line of intersection of the extended plane of the retinal meridian on which the image lies and the plane of the isogonal circle on which the spacial point lies. Since the plane of every isogonal circle as well as the plane of every retinal meridian passes through the center of rotation, their lines of intersection, which are lines of direction, must all pass through the center of rotation. This is another proof that every line of direction is a radius of retinal curvature prolonged.

It only remains now for me to show that every member of my large family of cortical and basal brain centers is real and not imaginary. This I can do by a further study of Figure 3. In this figure, C is the direct point of fixation on the circle B-C-D. In both intrinsic and pseudo-esophoria, the visual axes would tend to cross at some point within the circle, but this too early crossing is prevented by neuricity sent from some center or centers in the

brain to the two externi. Since there is no divergence voluntary center in control of the two externi, each of these muscles must be controlled by an individual involuntary center at the base of the brain. these are the right and left fourth basal centers, duction centers for the externi and under control of the fusion faculty of the mind. These two centers send just enough neuricity to their respective externi to compel intersection of the visual axes at C.

Again, if there is exophoria, the visual axes would tend to cross at some point beyond C, but the intersection beyond the chosen point of view is prevented by the two basal fusion centers for the two interni, these fusion centers, the right and left third basal centers, supplementing the neuricity from the third conjugate or convergence center so as to force intersection of the visual axes at C.

If the point of fixation of the visual axes of esophoric eyes is to be changed from C to A, on the same circle, three brain centers, two of them conjugate and one basal, must participate. Convergence at the same angle must be maintained by the third conjugate center, and the visual axes must be moved to the left by the left externus and the right internus, these being stimulated to do so, in part, by neuricity from the fifth conjugate center, but in part also by neuricity from the left fourth basal center to the left externus. One of the three muscles concerned, namely, the left internus, in this changing of the points of view, is under a single stimulus, the source being the third conjugate center. The right internus receives an equal convergence stimulus, but it also receives neuricity from the fifth conjugate center, the purpose of which is to rotate the right eye directly to the left. The left externus also receives neuricity from a double source, the one source being the fifth conjugate center, the other source being the left fourth basal center. Except for the supplemental neuricity from the left fourth basal center, the left visual axis would not move so fast as the right; hence they could not reach A at the same time, nor could the same angle of convergence be maintained throughout the rotation. It can not be denied that a weak muscle must have more neuricity than a strong muscle for the accomplishment of a given work. A conjugate center gives equal quantities of neuricity to the two muscles under its control; hence if one of a pair is weaker than the

other, there must be an individual fusion center for the weaker muscle, from which must come the supplemental neuricity.

In the next place, granting that there is lateral orthophoria, there is a need for individual basal fusion centers in all cases of hyperphoria. Let there be left hyperphoria and right cataphoria, of each 5°, with C as the point to be fixed. The interni are ready to respond perfectly to neuricity from a single center, the third conjugate. Tonicity of the superior and inferior recti of the left eye would place its visual axis in the plane of a secondary isogonal circle elevated 5° above the plane of the primary circle; the tonicity of the superior and inferior recti of the right eye would place its visual axis in the plane of a secondary isogonal circle 5° below the primary plane. Diplopia must follow without intervention of nerve force, and whence comes this force? Not from the first conjugate center, for this would elevate both eyes. Not from the second conjugate center, for this would depress both eyes. In neither case would the two axes be placed in the primary plane. To prevent diplopia the right first basal center must send neuricity to the weak superior rectus and thus make it elevate the visual axis into the primary plane; and the left second basal center must send neuricity to the weak inferior rectus and thus make it depress its visual axis into the primary plane. Thus the visual axes are brought into the plane of the primary isogonal circle by the two basal fusion centers, allowing the third conjugate center to converge them at C. with binocular single vision as a result.

In every possible binocular rotation the ocular muscles have one common task to perform, namely, the keeping of the two visual axes and the two horizontal retinal meridians in the plane of the primary isogonal circle, and the converging of these axes on some point on this circle, thus making of the single primary isogonal circle and the infinite number of secondary isogonal circles, all monoscopteric circles, or circles of binocular single vision.

The centers concerned in any rotation of any pair of eyes whether these eyes be orthophoric or heterophoric, can be known, and the work done by these centers can be understood by any oculist who sets himself to the task. It would be a pleasure to me to point them out, but this paper has already grown too long.

The aim of the treatment of all heterophorias is to give equal

tonicity to the two muscles of every pair so that the basal or fusion centers may have no abnormal work to do in planing the visual axes and horizontal retinal meridians and in shifting and converging the visual axes at a point on the primary isogonal circle.

Listing's plane and law, Helmholtz's poles. law of direction and nodal point, Muller's horopter, and the multitude of errors growing out of these must be forgotten or ignored if one is to have any accurate knowledge of ocular rotations. The same is true if one wishes to know how to detect and deal with heterophoric conditions